2.2 GHZ SURFACE ACOUSTIC WAVE (SAW) OSCILLATOR DEVELOPMENT

KU-BAND FREQUENCY SOURCE DEVELOPMENT

FINAL REPORT

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Goddard Space Flight Center
Greenbelt, Maryland 20771

TRW
DEFENSE AND SPACE SYSTEMS GROUP

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PROGRAM OBJECTIVES

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- DESIGN AND FABRICATE TWO 2.2 GHZ SAW OSCILLATORS USING $A\ell N/A\ell_2O_3$ DELAY LINES
- FABRICATE TWO 2.2 GHZ $A\ell N/A\ell_2O_3$ DELAY LINES FOR OSCILLATORS
- FABRICATE AND EVALUATE TWO WAFER RUNS OF 2.2 GHZ TED DEVICES
- DEVELOP A 15 GHZ FREQUENCY SOURCE

SUMMARY OF RESULTS

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- FABRICATED AND TESTED TWO 2.2 GHZ SAW OSCILLATORS USING $A\ell N/A\ell_2O_3$ DELAY LINES
- FABRICATED AND TESTED A 15 GHZ SOURCE USING KU-BAND FET OSCILLATOR PHASE-LOCKED TO A 2.2 GHZ SAW REFERENCE OSCILLATOR
- FABRICATED AND EVALUATED TWO WAFER RUNS OF 2.2 GHZ TED DEVICES

AlN/Al_2O_3 STUDY OBJECTIVES

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- DEVELOP A SAW DELAY LINE CAPABILITY USING A MATERIAL, ALUMINUM NITRIDE ON SAPPHIRE (AlN/Al_2O_3), WITH A HIGH SURFACE ACOUSTIC WAVE VELOCITY

- EXTEND AlN/Al_2O_3 SAW TECHNOLOGY TO 2.2 GHZ

- FABRICATE TWO 2.2 GHZ AlN/Al_2O_3 SAW DELAY LINES WHICH WILL BE USED IN FABRICATION OF 2.2 GHZ SAW OSCILLATORS

ALUMINUM NITRIDE/SAPPHIRE SAW MATERIAL

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- ALUMINUM NITRIDE (AℓN) IS GROWN EPITAXIALLY ON A SAPPHIRE ($A\ell_2 0_3$) SUBSTRATE
- AℓN/$A\ell_2 0_3$)IS A COMPOSITE SYSTEM. THE AℓN LAYER IS TYPICALLY LESS THAN ONE WAVELENGTH THICK AND THEREFORE THE ACOUSTIC WAVE PROPAGATES THROUGH BOTH THE AℓN FILM AND THE SAPPHIRE SUBSTRATE
- SURFACE ACOUSTIC WAVE VELOCITY IS APPROXIMATELY TWICE THAT OF ST CUT QUARTZ
- THE RATIO OF THE AℓN LAYER THICKNESS (T) TO THE ACOUSTIC WAVELENGTH (λ) DETERMINES THE SURFACE ACOUSTIC WAVE VEL-OCITY AND THE TEMPERATURE COEFFICIENT OF DELAY
- THE DEPENDENCE OF THE SAW VELOCITY UPON T/λ MAKES IT POS-SIBLE TO FABRICATE SAW DEVICES WITH DIFFERENT OPERATING FREQUENCIES FROM THE SAME PHOTOMASK BY VARYING THE AℓN FILM THICKNESS

GROWTH OF AℓN/Aℓ_2O$_3$

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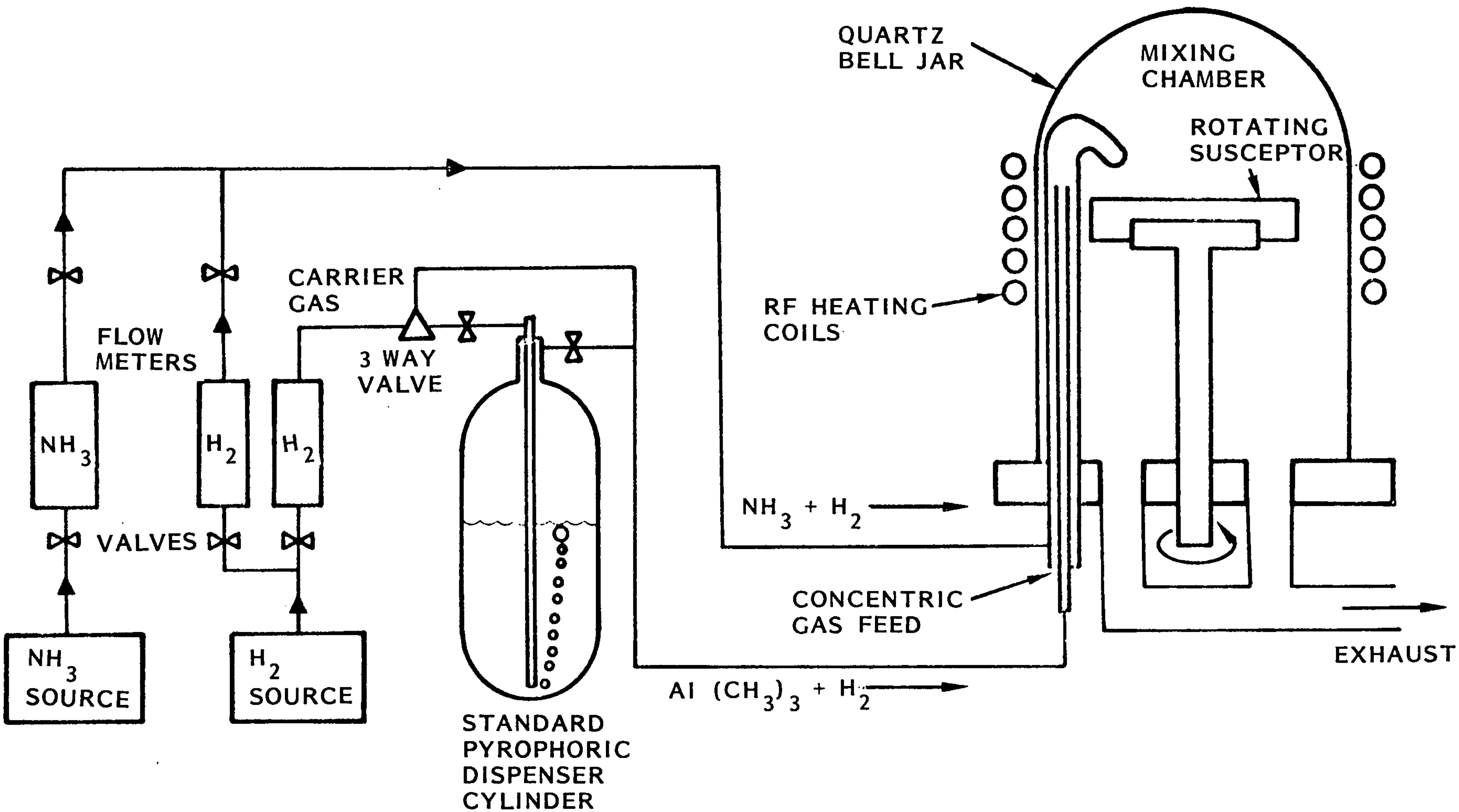


VAPOR EPITAXIAL REACTOR

SAW VELOCITY DEPENDENCE ON T/λ RATIO

Aluminum nitride on sapphire is a composite structure and therefore the surface acoustic wave velocity is dependent upon the thickness of the AℓN layer. The figure shows the relationship between velocity and the AℓN thickness to wavelength ratio (t/λ). The open circles show the original data taken by Lakin, et al. The closed triangles are TRW's measurements. For t/λ ratios of 0.75 and less, the two sets of data agree reasonably well. For t/λ's of >0.75, TRW's data shows a leveling off of velocity while Lakin's data shows a continued decrease in velocity. The exact reason for this result is not known and is the subject of continued investigation.

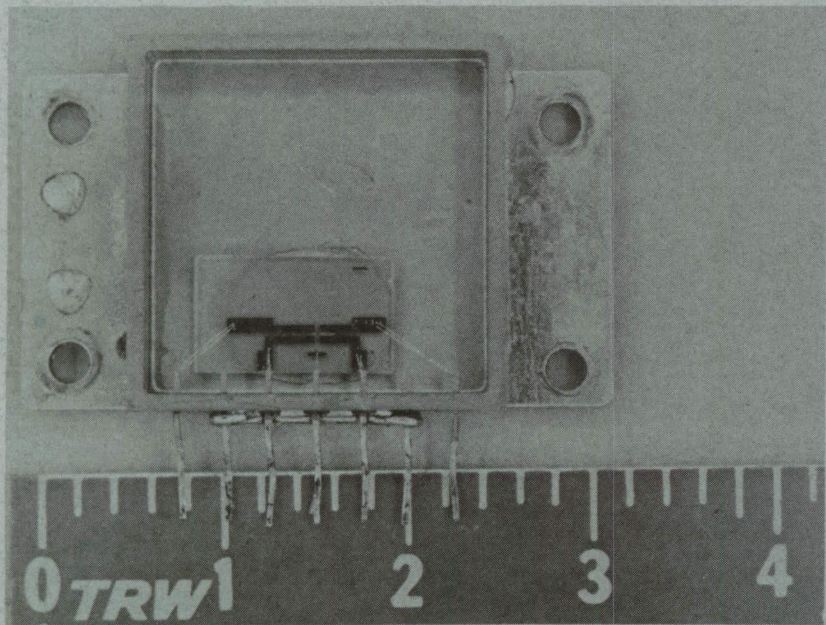
TEMPERATURE COEFFICIENT OF DELAY

Aluminum nitride/sapphire is a layered system and therefore the temperature coefficient of delay is a function of the thickness of the $A\ell N$ film. The curve below summarizes previous measurements (Lakin, et al) and the results of TRW's investigation.

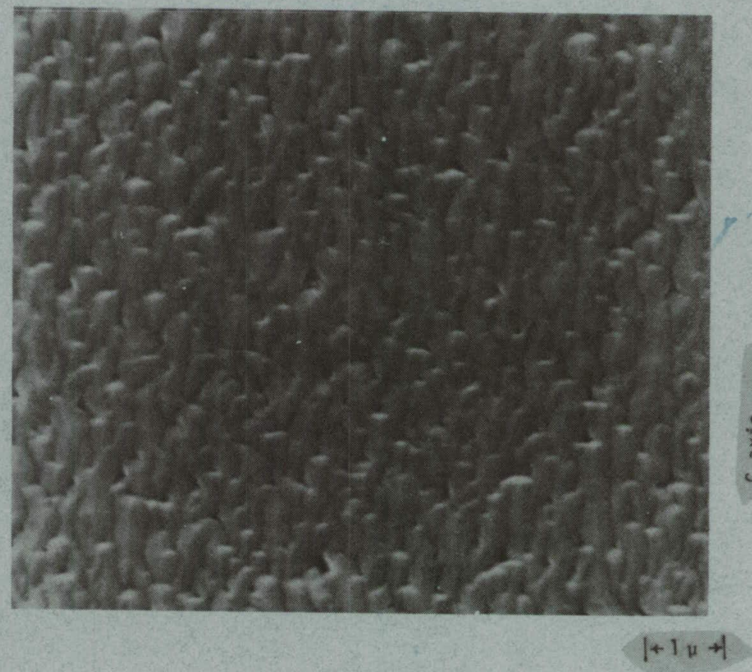
At the start of this program, an extrapolation of existing data predicted that for a t/λ of ~0.7, the first order temperature coefficient of delay would go to zero. The maximum t/λ achieved at the time was ~0.6. [At the lower frequencies (<500 MHz) that the previous measurements had been performed, the maximum growable $A\ell N$ film thickness (<5 micron) had prevented the fabrication of high t/λ ratio delay lines].

In the course of this investigation, delay lines with ratios as high as 1.0 were evaluated. As the TRW data (triangles) shows, the coefficient did not go to zero as expected, but rather reached an asymptotic value of 22 ppm/^{o}C. The reason for this result is not yet known but is the subject of continued investigation.

2.2 GHZ SAW DELAY LINE



2.2 GHZ SAW DELAY LINE



SEM PHOTOGRAPH OF AℓN EPITAXIAL FILM.
(10,000 X MAGNIFACATION)

SAW OSCILLATOR DELAY LINE DATA

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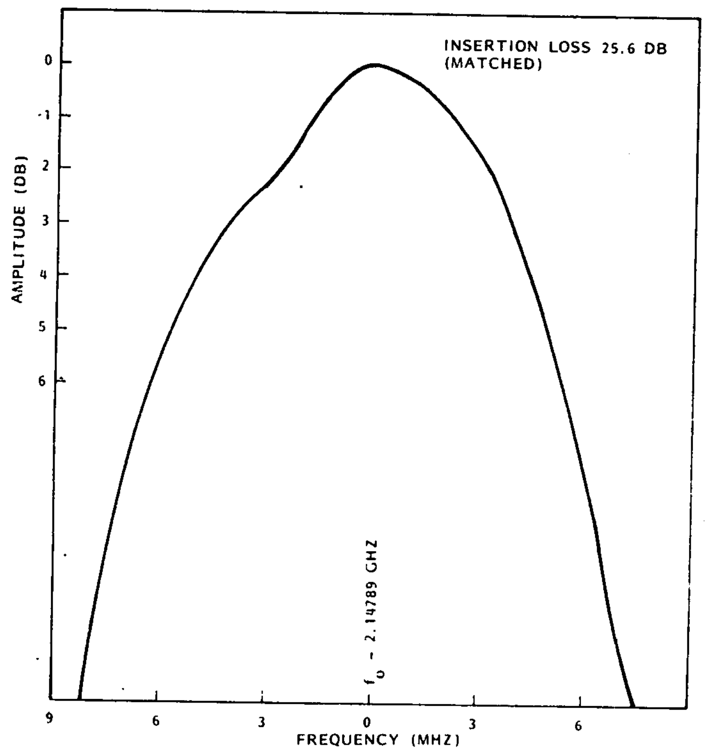

SAW DELAY LINE DATA SUMMARY

PARAMETER	SAW 1	SAW 4
CENTER FREQUENCY	2.1789 GHZ	2.1478 GHZ
BANDWIDTH (3 DB)	4.35 MHZ	8.1 MHZ
INSERTION LOSS	27.5 DB	25.6 DB

2.2 GHZ SAW OSCILLATOR DEVELOPMENT OBJECTIVES

TRW
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- EVALUATE AND REFINE THE SAW OSCILLATOR DESIGN FOR OPTIMUM PERFORMANCE AT 2 GHZ
- EVALUATE TEMPERATURE COMPENSATION TECHNIQUES
- FABRICATE TWO DELIVERABLE 2.2 GHZ SAW OSCILLATORS
- CHARACTERIZE TEMPERATURE, PHASE NOISE, AND AGING CHARACTERISTICS OF TWO DELIVERABLE OSCILLATORS

2.2 GHZ SAW OSCILLATOR

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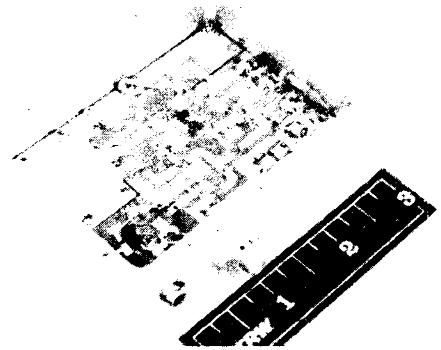

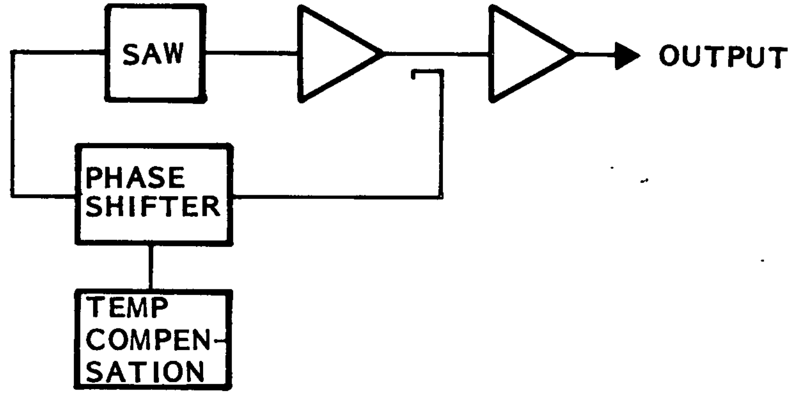

FEATURES

- LOW POWER CONSUMPTION
- SMALL SIZE
- LOW PHASE NOISE
- HIGH STABILITY

KEY PARAMETERS

FREQUENCY	2.149 GHZ
POWER OUTPUT	+17 DBM
TEMPERATURE RANGE	0 TO 120°F
PHASE NOISE	-102 DBC AT 10 KHZ
DC POWER	2.5 WATTS
SIZE	3.7 X 2.7 X 0.85 IN
WEIGHT	227 GRAMS

2.2 GHZ SAW OSCILLATOR DATA SUMMARY

TRW DEFENSE AND SPACE SYSTEMS GROUP

PARAMETER	REQUIREMENT	PERFORMANCE
POWER OUTPUT	0 TO +20 DBM	+17 DBM
FREQUENCY	2.2 GHZ	2.149
FREQUENCY SETABILITY	±0.15 3 DB BW	
TEMPERATURE STABILITY -20 to 50°C	±0.002%	±0.0016%
AGING	1×10^{-8} PP DAY	2.25×10^{-6} PP DAY
PHASE NOISE DBC/HZ		
10 HZ		-16 DBC
100 HZ		-41 DBC
1 KHZ		-73 DBC
10 KHZ		-102 DBC
100 KHZ		-126 DBC
1 MHZ		-148 DBC
SAW UNLOADED Q	≥2000	
SAW INSERTION LOSS	≤20 DB	

SURFACE ACOUSTIC WAVE OSCILLATOR THEORY OF OPERATION

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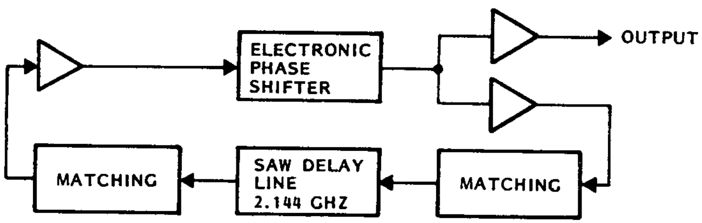
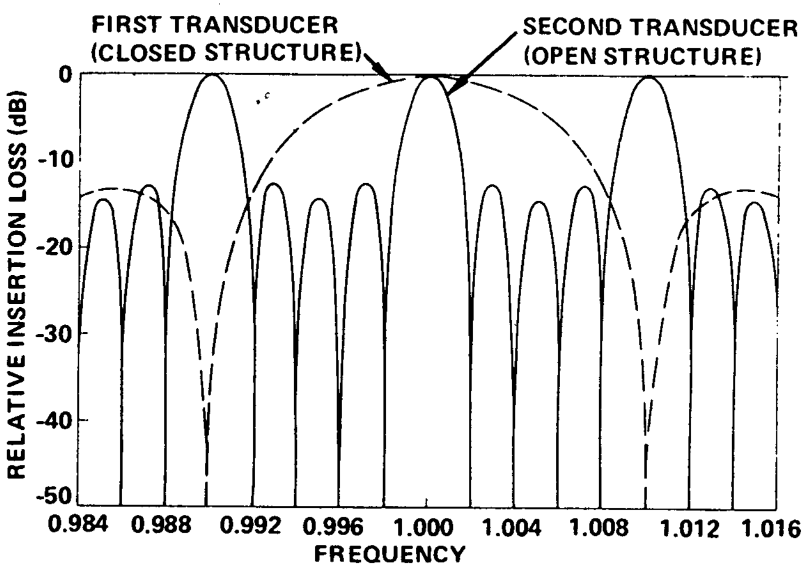
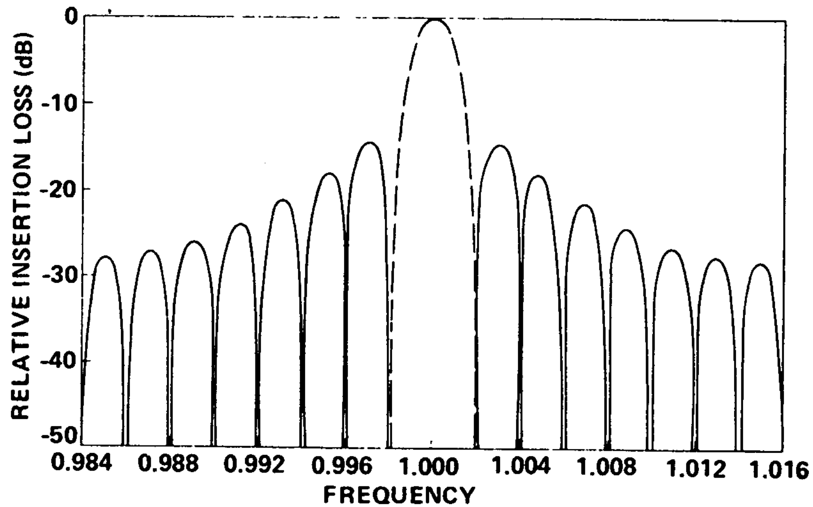


SAW OSCILLATOR BLOCK DIAGRAM

- SAW OSCILLATOR IMPLEMENTED WITH A SURFACE ACOUSTIC WAVE DELAY LINE FILTER CONNECTED IN A FEEDBACK LOOP AROUND A MICROWAVE AMPLIFIER
- LOOP WILL OSCILLATE AT FREQUENCY AT WHICH PATH LENGTH OF FEEDBACK LOOP IS AN INTEGER NUMBER OF WAVE LENGTHS AND THE LOOP GAIN IS GREATER THAN ONE
- SAW TRANSDUCERS ARE CONFIGURED TO CANCEL UNDESIRED RESPONSES
- EXTREMELY NARROW PASS BAND OF SAW DELAY ENSURES ONLY FREQUENCY OF OSCILLATION IS POSSIBLE
- FREQUENCY STABILITY OF OSCILLATOR IS DETERMINED BY SAW DELAY LINE ($>500\lambda$ COMPARED TO $<2\lambda$ FOR AMPLIFIER AND MATCHING CIRCUITRY)



INDIVIDUAL TRANSDUCER FREQUENCY



COMPOSITE STRUCTURE FREQUENCY RESPONSE

SAW OSCILLATOR TEMPERATURE COMPENSATION

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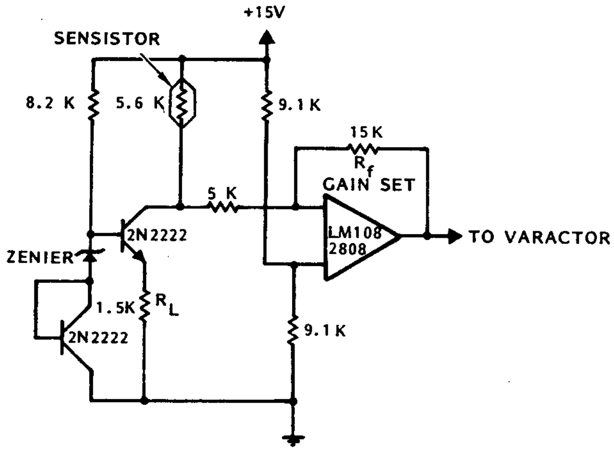
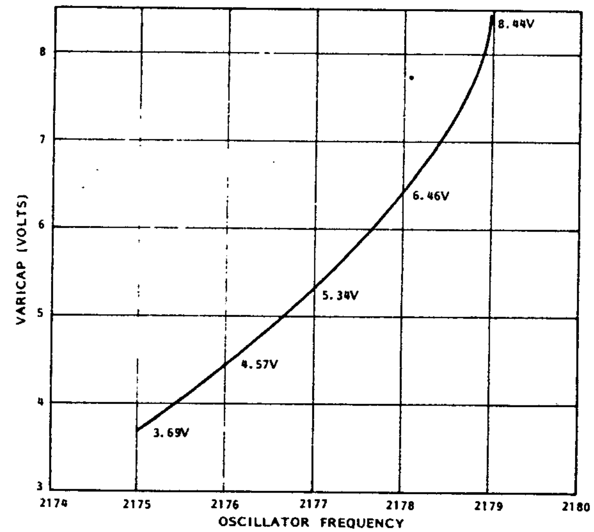


TEMPERATURE COMPENSATION CIRCUIT



SAW FREQUENCY VERSUS CONTROL VOLTAGE

- SAW OSCILLATOR FREQUENCY IS TEMPERATURE STABILIZED BY ADJUSTING ITS OPERATING FREQUENCY TO OFFSET TEMPERATURE EFFECTS

- A SENSISTOR MOUNTED ON SAW DELAY LINE SENSES TEMPERATURE OF DELAY LINE

- CORRECTION VOLTAGE IS INVERTED AND SHAPED BY OPERATIONAL AMPLIFIER AND APPLIED TO FREQUENCY CONTROL INPUT OF SAW OSCILLATOR

SAW OSCILLATOR TEMPERATURE DATA

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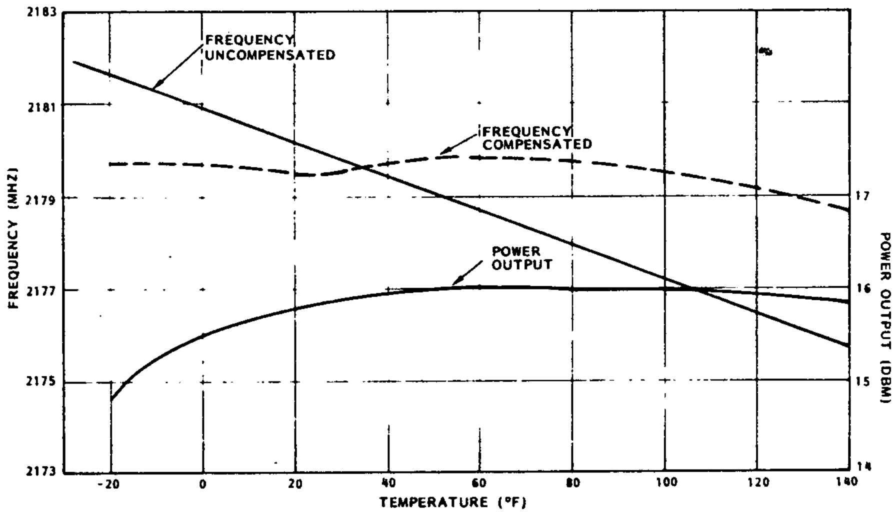
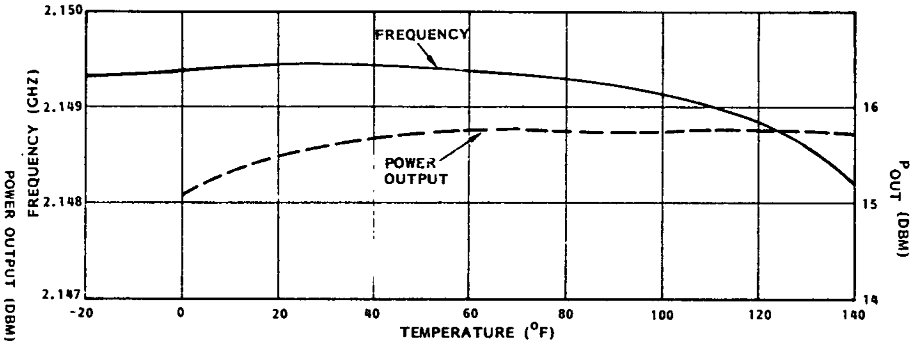


SAW OSCILLATOR 1



SAW OSCILLATOR 2

TEMPERATURE PERFORMANCE DATA SUMMARY

PARAMETER	OSCILLATOR 1	OSCILLATOR 2
FREQUENCY	2179 MHZ	2148 MHZ
TEMPERATURE STABILITY 0 TO 120°F	±0.0016 PERCENT	±0.0017 PERCENT
OUTPUT POWER	+16 DBM	+15.75 DBM
OUTPUT POWER VARIATION	+0, -0.5 DB	+0, -0.6 DB

2.2 GHZ SAW OSCILLATOR PHASE NOISE

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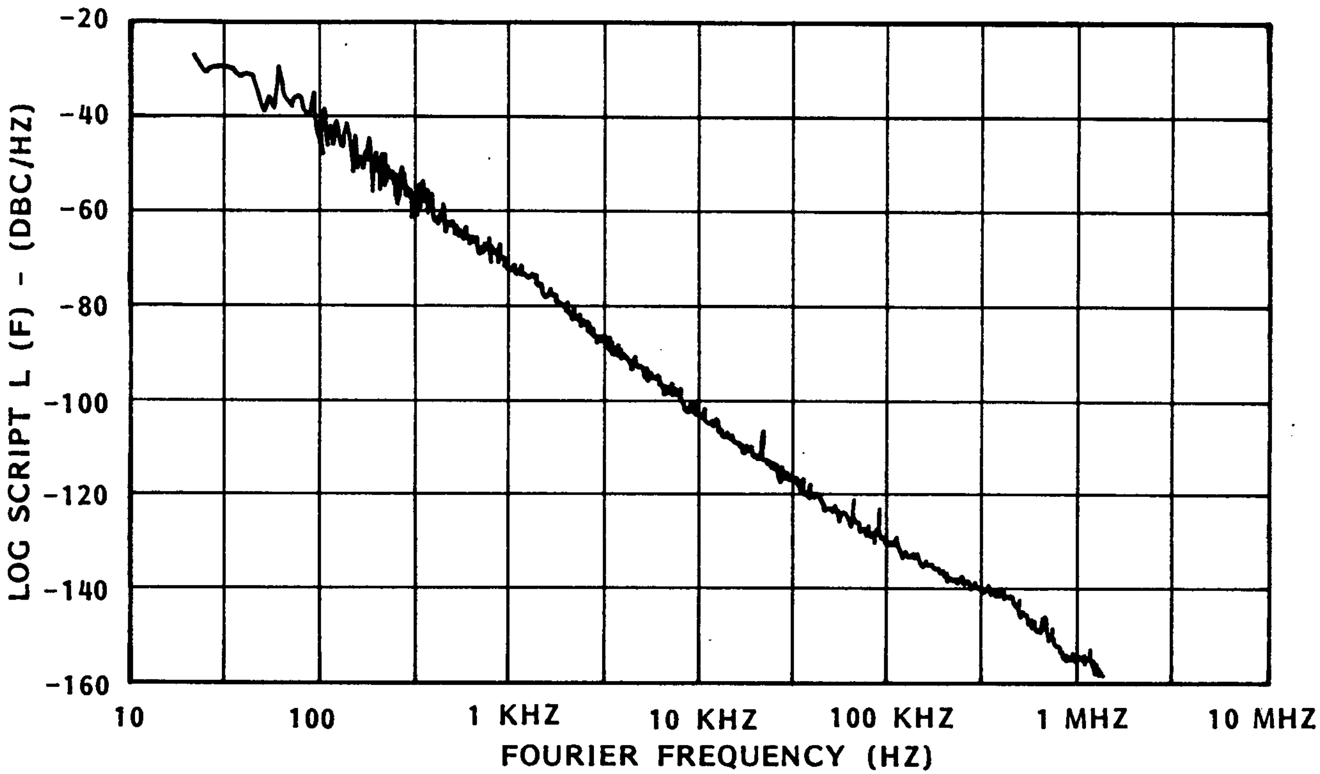

TEST FREQUENCY = 2.148 GHZ

KU-BAND SOURCE OBJECTIVES

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- IDENTIFY OPTIMUM KU-BAND SOURCE CONFIGURATION
- DESIGN AND FABRICATE A KU-BAND FREQUENCY SOURCE WHICH USES A SAW OSCILLATOR AS A FREQUENCY REFERENCE
- EXTENSIVELY CHARACTERIZE THE KU-BAND FREQUENCY SOURCE
- FABRICATE AND EVALUATE TED DEVICES AS FREQUENCY DIVIDER ELEMENTS

KU-BAND FREQUENCY SOURCE CONFIGURATION STUDY

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- TWO GENERAL CIRCUIT TECHNIQUES WERE EVALUATED TO SELECT A BASELINE APPROACH
- TWO POTENTIAL CIRCUIT TECHNIQUES UTILIZE EITHER FREQUENCY MULTIPLICATION OR DIVISION TO EFFECT A PHASE COMPARISON BETWEEN REFERENCE AND OUTPUT FREQUENCY
- TWO TECHNIQUES WERE COMPARED BASED ON
  - SIZE
  - WEIGHT
  - POWER
  - COMPLEXITY
  - TEMPERATURE PERFORMANCE
  - PHASE NOISE

X7 MULTIPLIER APPROACH

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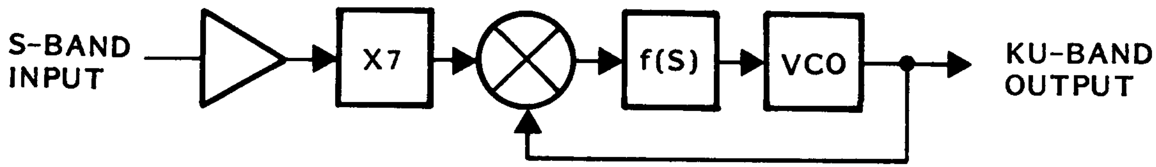


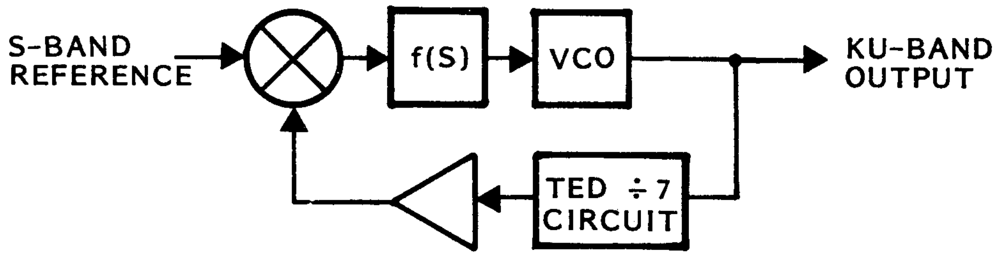
A +17 DBM S-BAND AMPLIFIER DRIVES A X7 MULTIPLIER WHICH PROVIDES A +7 DBM KU-BAND REFERENCE SIGNAL TO THE PHASE DETECTOR. THE KU-BAND OUTPUT SIGNAL IS GENERATED BY A PHASE-LOCKED KU-BAND FET VOLTAGE CONTROLLED OSCILLATOR

CIRCUIT ELEMENTS

- MEDIUM POWER S-BAND PREAMPLIFIER
- X7 STEP RECOVERY DIODE MULTIPLIER
- 15 GHZ PHASE DETECTOR
- LOOP AMPLIFIER ACQUISITION CIRCUIT
- 15 GHZ FET VOLTAGE CONTROLLED OSCILLATOR

TED DIVIDER APPROACH

TRW DEFENSE AND SPACE SYSTEMS GROUP



THE KU-BAND OUTPUT OF A KU-BAND FET VCO IS FREQUENCY DIVIDED BY A FACTOR OF 7 AND PHASE COMPARED WITH THE S-BAND REFERENCE SIGNAL. THE ERROR VOLTAGE OUTPUT OF THE S-BAND PHASE DETECTOR IS USED TO PHASE-LOCK THE KU-BAND VCO TO REFERENCE INPUT

<u>CIRCUIT ELEMENTS</u>

- S-BAND PHASE DETECTOR
- TED ÷ 7 CIRCUIT
- 15 GHZ FET VOLTAGE CONTROLLED OSCILLATOR
- LOOP AMPLIFIER AND ACQUISITION CIRCUIT
- S-BAND AMPLIFIER

STUDY CONCLUSIONS

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FIVE PRIMARY FACTORS WERE SIGNIFICANT IN COMPARING ADVANTAGES OF EACH CIRCUIT CONFIGURATION

- TED DIVIDER IS 70 PERCENT SMALLER AND LIGHTER THAN MULTIPLIER
- TED DIVIDER DRAWS 75 PERCENT AS MUCH POWER AS MULTIPLIER
- MULTIPLIER HAS A SLIGHT PHASE NOISE ADVANTAGE OVER TED APPROACH
- TED HAS SEVERE TEMPERATURE COMPENSATION PROBLEMS AS COMPARED TO THE MULTIPLIER
- TED TECHNOLOGY HAS NOT YET MATURED TO HI-REL SPACECRAFT STATUS

BASED PRIMARILY ON TEMPERATURE COMPENSATION PROBLEM ASSOCIATED WITH TED DIVIDER CIRCUIT THE MULTIPLIER APPROACH WAS SELECTED AS BASELINE DESIGN

FET OSCILLATOR DESIGN GOALS

TRW

- COMPATIBLE WITH SMALL, LIGHTWEIGHT HYBRID CONSTRUCTION
- UTILIZATION OF HYBRID MIC TECHNIQUES
- LOW PHASE NOISE
- PHASE NOISE PERFORMANCE MATHEMATICALLY PREDICTABLE
- HIGH Q RESONATOR
- MINIMUM POWER FROM +5, -5.2 VOLT SUPPLIES

FET VCO APPROACH

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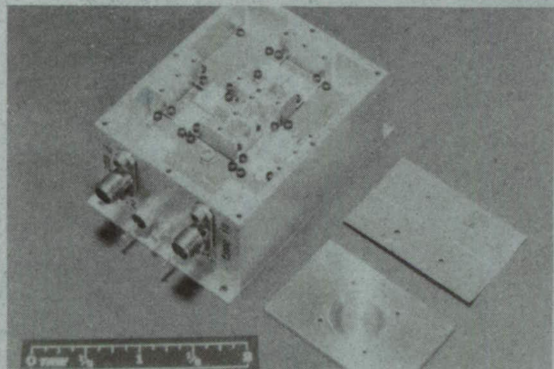
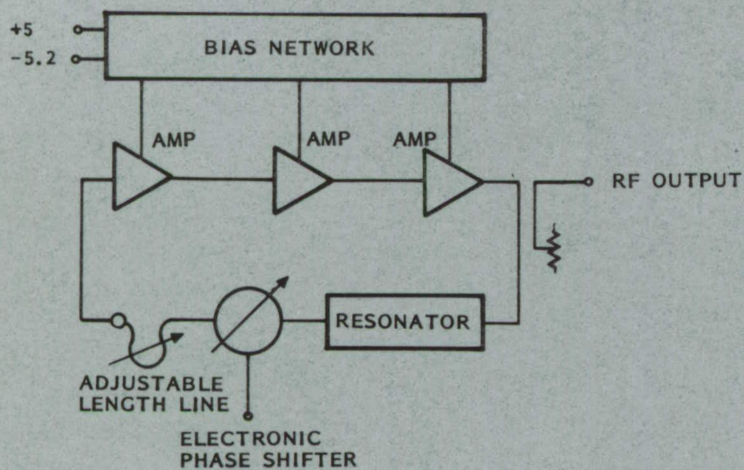
- EXAMINE AND CHOOSE BEST OSCILLATOR CONFIGURATION FOR MEETING GOALS, NEGATIVE RESISTANCE OSCILLATOR OR FEEDBACK LOOP OSCILLATOR
- EXAMINE AND CHOOSE BEST RESONATOR, MICROSTRIP, OR CAVITY
- ONCE THE FEEDBACK LOOP OSCILLATOR WITH A CAVITY RESONATOR WAS CHOSEN AS MOST VIABLE SOLUTION, A HYBRID COMPATIBLE SOURCE WAS DESIGNED
- SOURCE WAS BUILT AND TESTED SUCCESSFULLY, BUT PERFORMANCE OVER TEMPERATURE INDICATED IMPROVEMENT IN PHASE SHIFTER DESIGN AND CAVITY TEMPERATURE COEFFICIENT WOULD BE NECESSARY FOR OPERATION OVER FULL TEMPERATURE RANGE

KU-BAND FET VCO

TRW





FET OSCILLATOR BLOCK DIAGRAM

SPECIFICATIONS

OUTPUT FREQUENCY	15.0 GHZ
OUTPUT POWER	+5.5 DBM
TUNING VOLTAGE	-13 TO -2 VOLTS
TUNING RANGE	±3.0 MHZ
PHASE NOISE	-104 DBC/HZ AT 100 KHZ OFFSET
DC POWER	+5 V, 170 MW -5.2 V, 3 MW
SIZE	2.3 X 1.8 X 1.1 IN

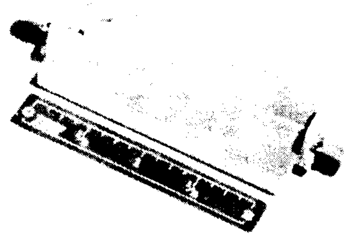
FEATURES

- EASILY ADJUSTABLE OUTPUT FREQUENCY
- PHASE LOCK CAPABILITY
- THIN CAVITY RESONATOR WITH LOADED Q OF 605
- HYBRID CIRCUIT COMPATIBLE DESIGN
- GOOD PHASE NOISE PERFORMANCE

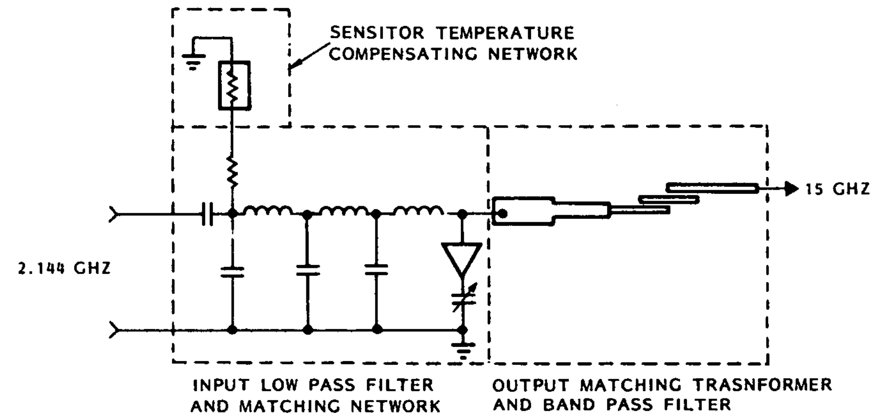
VCO PERFORMANCE SUMMARY

PARAMETER	CAPABILITY
FREQUENCY	15.0 GHZ
DC POWER	175 MW
RESONATOR Q	605
PHASE NOISE	
1 KHZ	-40 DBC/HZ
10 KHZ	-70 DBC/HZ
100 KHZ	-104 DBC/HZ
1 MHZ	-138 DBC/HZ
10 MHZ	-160 DBC/HZ
OUTPUT POWER	+5.5 DBM $\pm$0.6 DB
TUNING RANGE	$\pm$3 MHZ
TEMPERATURE RANGE	+20 TO 50°C

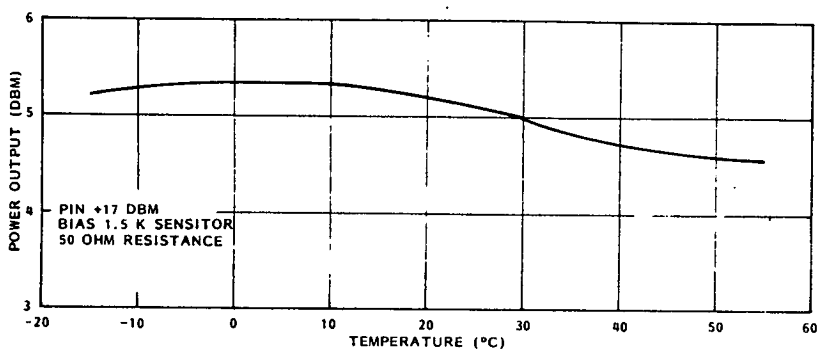
X7 15 GHZ MULTIPLIER



15 GHZ X7 MICROSTRIP MULTIPLIER



SCHEMATIC DIAGRAM



MULTIPLIER OUTPUT POWER VERSUS TEMPERATURE

PERFORMANCE

- INPUT FREQUENCY 2.144 GHZ
- OUTPUT FREQUENCY 15 GHZ
- INPUT POWER +17 DBM
- OUTPUT POWER +5 DBM
- 3 DB BANDWIDTH (OUTPUT) +315 MHZ, -420 MHZ
- VSWR <1.4:1

15 GHZ PHASE DETECTOR

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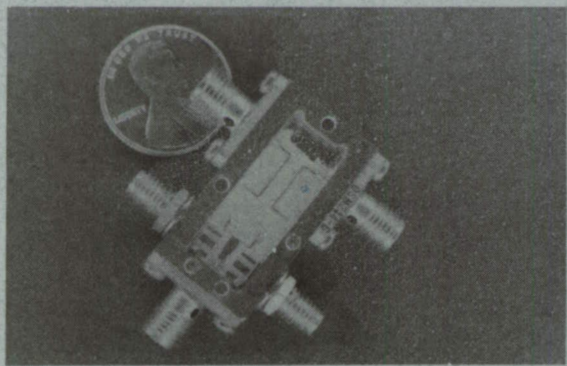
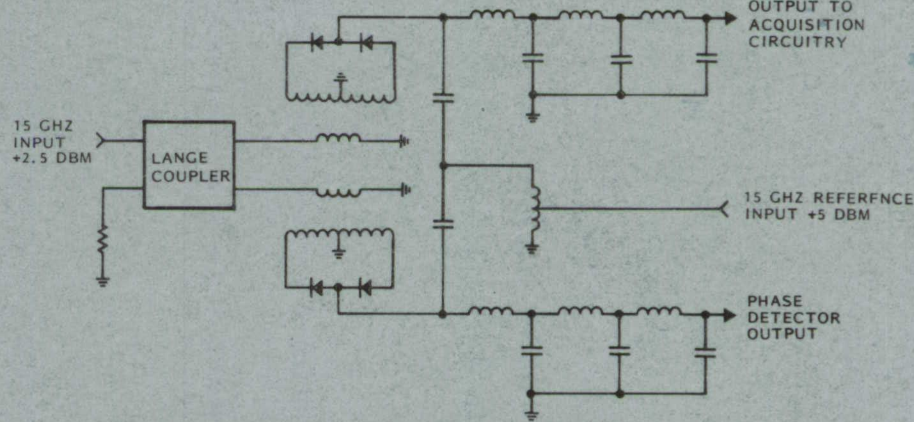


15 GHZ MICROSTRIP PHASE DETECTOR



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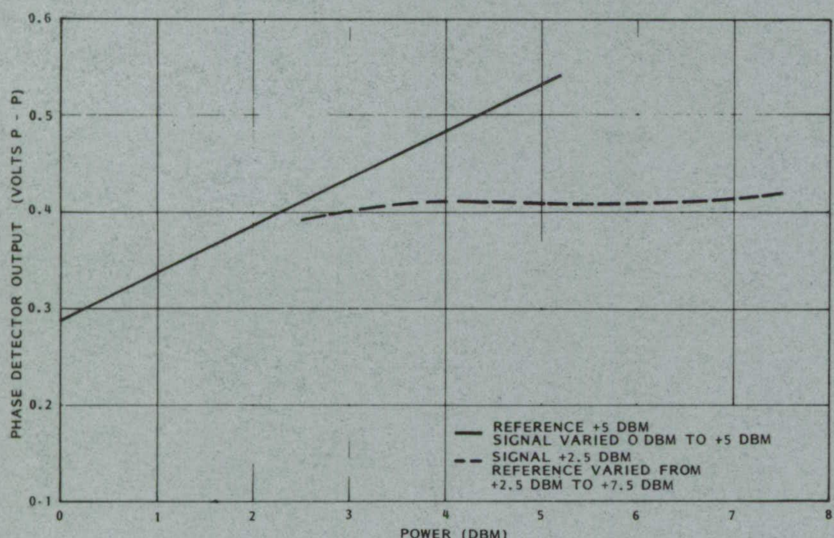

PHASE DETECTOR SENSITIVITY

PERFORMANCE

- INPUT FREQUENCY 15 GHZ
- INPUT POWER +5 DBM
- SENSITIVITY 4 MV/DEG
- VSWR 2.0:1

KU-BAND FREQUENCY SOURCE PERFORMANCE SUMMARY

TRW
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PARAMETER	PERFORMANCE
FREQUENCY	15.035 GHZ
TEMPERATURE STABILITY	$\pm$0.023 PERCENT ($\pm$3.36 MHZ)
PHASE NOISE	
100	-24 DBC/HZ
1 KHZ	-53 DBC/HZ
10 KHZ	-69 DBC/HZ
100 KHZ	-96 DBC/HZ
1 MHZ	-132 DBC/HZ
OUTPUT POWER	-2.5 DBM $\pm$0.5 DB
DC POWER	6.1 WATTS
TEMPERATURE RANGE	65°F TO 118°F
SPURIOUS (10 TO 18 GHZ)	< -60 DBC

KU-BAND FREQUENCY SOURCE

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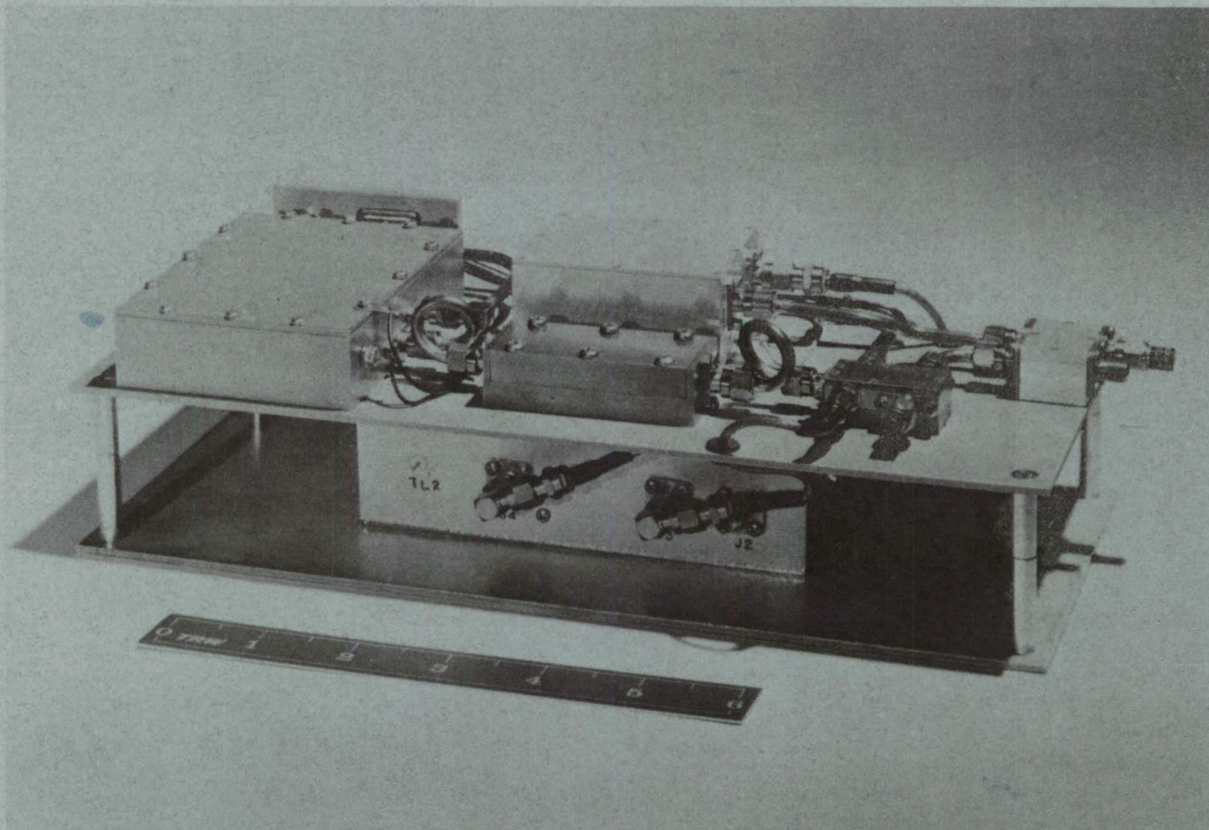

TED DIVIDER DEVELOPMENT PROGRAM
OBJECTIVES AND SUMMARY

TRW
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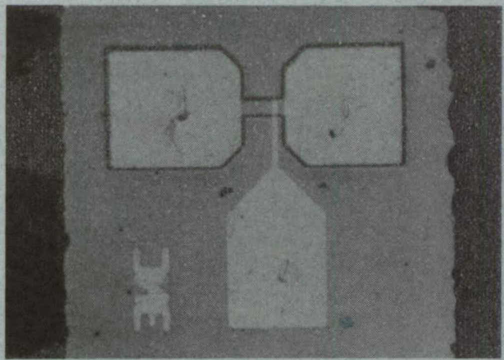
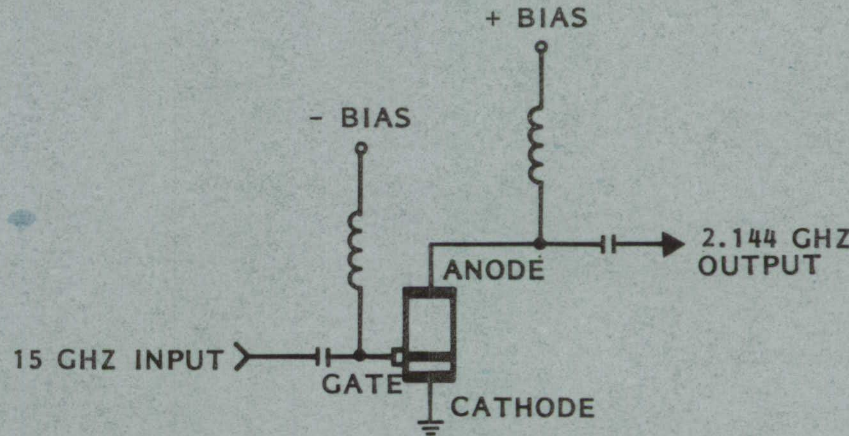
- TASK OBJECTIVES
  - SCALE EXISTING 1 AND 5 GHZ TED DESIGNS FOR 2.144 GHZ OPERATION
  - FABRICATE A 2.144 GHZ TED DEVICE MASK
  - FABRICATE 2 WAFER RUNS OF 2.144 GHZ TED DEVICES
  - CHARACTERIZE TED DEVICES AS 15 GHZ FREQUENCY DIVIDERS
  - INVESTIGATE POSSIBILITY OF USING TED DIVIDER AS PART OF A KU-BAND SOURCE

- TASK SUMMARY
  - TWO WAFER RUNS OF 2.144 GHZ TED DEVICES WERE FABRICATED
  - TED DEVICES WERE CHARACTERIZED IN AN RF CIRCUIT AS 15 GHZ DIVIDERS
  - TEMPERATURE DATA INDICATED TED WAS UNUSABLE AS A PRACTICAL DEVICE IN ITS PRESENT FORM/CIRCUIT

TED FREQUENCY DIVIDER



2.144 GHZ TED

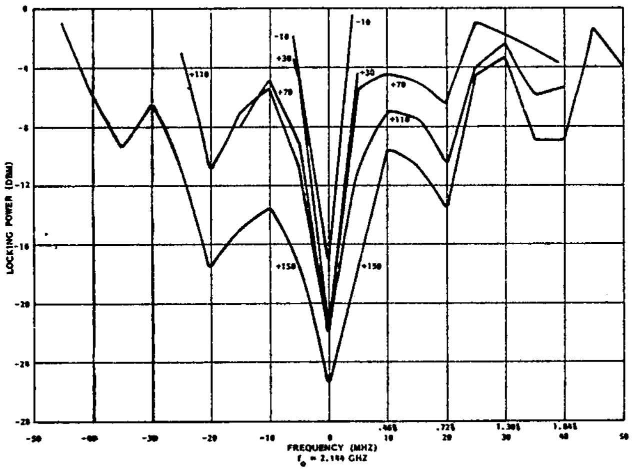


TED DIVIDER CIRCUIT

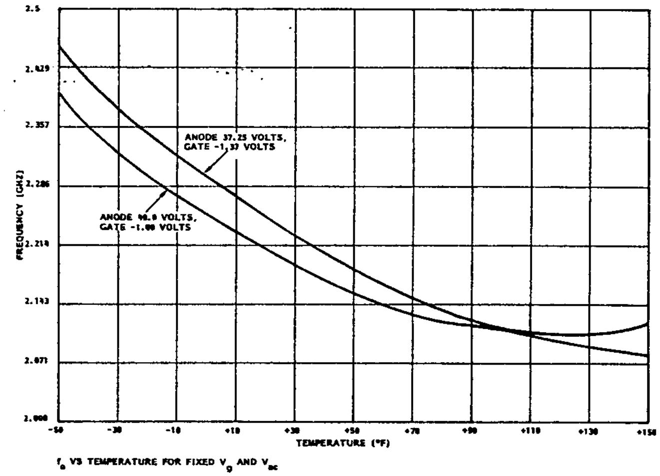
- A TED FREQUENCY DIVIDER IS A TRW DEVELOPED CIRCUIT USING AN n–TYPE GaAs TED TRIODE
- OUTPUT FREQUENCY IS DETERMINED BY TRANSIT TIME BETWEEN ANODE AND CATHODE
- INPUT (INTEGER MULTIPLE OF OUTPUT FREQUENCY) TRIGGERS AN ELECTRON DOMAIN IN DEVICE
- A DOMAIN, ONCE TRIGGERED, MUST REACH THE CATHODE BEFORE A NEW ONE CAN BE INITIATED
- OUTPUT IS THEREFORE SUBHARMONICALLY COHERENT WITH THE INPUT SIGNAL

TED DIVIDER DATA SUMMARY

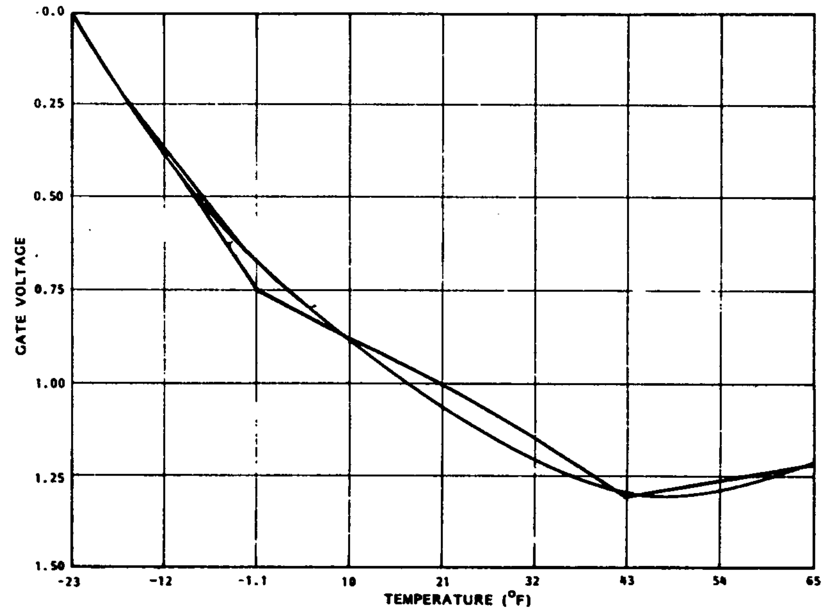
TRW



LOCKING BANDWIDTH VERSUS TEMPERATURE AND INPUT POWER



f_o VERSUS TEMPERATURE



V_g VS T FOR FIXED V_{ac}
TO ACHIEVE 2.144 GHZ

GATE VOLTAGE VERSUS TEMPERATURE

TYPICAL DATA RANGES

f_o	2.1 to 2.4 GHZ
ANODE VOLTAGE	25 to 45 VOLTS
GATE VOLTAGE	0 to 4 VOLTS
LOCKING POWER (10 MHZ)	0 to -18 DBM
OUTPUT POWER	10 to -20 DBM

PROGRAM OBJECTIVES

The overall objective of this program was to develop a Ku-band frequency source which utilized a 2.2 GHz fundamental mode SAW oscillator as a frequency reference. As a part of the Ku-band frequency source development, four specific areas were addressed.

Several 2.2 GHz aluminum nitride on sapphire ($A\ell N/A\ell_2O_3$) SAW delay lines were fabricated. The 2.2 GHz SAW delay lines served as the frequency determining element in 2.2 GHz reference oscillator for the Ku-band source. Two 2.2 GHz SAW oscillators using the 2.2 GHz $A\ell N/A\ell_2O_3$ delay lines were designed and fabricated. One of the 2.2 GHz oscillators was used as the reference oscillator for the Ku-band source and the other as a stand-alone source.

A study was performed to identify the optimum technique to configure the Ku-band source. Two techniques which phase-locked a Ku-band FET to the 2.2 GHz SAW oscillator were identified. Common to both approaches was the requirement to perform a phase comparison of the 2.2 GHz reference frequency and the 15 GHz output frequency.

The first technique was to multiply the 2.2 GHz times seven to 15 GHz and perform the phase detection at Ku-band. The second technique was to frequency divide the 15 GHz signal by seven and perform the phase detection at S-band.

Due to the design maturity, it was decided to configure the source using the multiplier approach. In parallel, a program to improve upon the TED devices and divider circuit was initiated. In order to evaluate this device, two wafer runs of TED devices were fabricated and tested.

The final task of the program was the assembly and test of the complete Ku-band source.

SUMMARY OF RESULTS

Two 2.2 GHz SAW oscillators using aluminum nitride on sapphire ($A\ell N/A\ell_2O_3$) delay lines were fabricated. The oscillators were electronically temperature compensated and characterized. One of the oscillators was used as the frequency reference for the Ku-band source; the second oscillator is available for continued evaluation.

A 15 GHz frequency source was designed and fabricated. The 15 GHz source consists of a Ku-band FET oscillator which is phase-locked to the frequency multiplied (X7) output of the 2.2 GHz SAW reference source. The Ku-band source was built using microstrip circuit designs, which are hybrid compatible.

Two wafer runs of 2.2 GHz TED devices were fabricated and evaluated. The devices were mounted on microstrip test substrates and evaluated as 15 GHz divide by 7 circuits. The device evaluation indicated that in their present form the TED is not a practical circuit element.

ALUMINUM NITRIDE/SAPPHIRE STUDY OBJECTIVES

The overall objective of the study was to demonstrate the use of a new, high velocity SAW substrate material for delay lines operating above 2 GHz. In order to reach this objective, four specific tasks were undertaken:

1. $A\ell N/A\ell_2O_3$ substrate material growth
2. 2.2 GHz SAW delay line design
3. 2.2 GHz submicron photomask fabrication
4. 2.2 GHz delay line fabrication.

$A\ell N/A\ell_2O_3$ substrates are not commercially available and therefore TRW grew all of the material required for the program. $A\ell N$ is grown epitaxially on sapphire substrates using a process similar to that used by the semiconductor industry. Prior to photomask design, the delay line was extensively modeled using both equivalent circuit and delta function techniques. The modeling provided the predicted impedance levels and frequency response for the delay line.

The submicron photomask for the delay line was fabricated at TRW using an optical generation technique. A combination pattern generator and image repeater with 10X reticle lense was used to generate the dark field chrome mask. The 2.2 GHz delay lines were fabricated using the lift-off technique. Several delay lines of varying t/λ ratios were fabricated to investigate the relationship between t/λ and velocity and temperature coefficient.

KEY FEATURES OF ALUMINUM NITRIDE/SAPPHIRE

The 2.2 GHz SAW delay lines for this program were fabricated on aluminum nitride/sapphire substrates. The key advantage of this material is its high SAW velocity, roughly 1.9 times that of ST cut quartz. This means that for a given set of photomask dimensions, a delay line will operate at 2 GHz when fabricated on $A\ell N/A\ell_2O_3$ compared to 1.1 GHz for ST cut quartz. Sensitivity to fabrication errors is also reduced by the same factor.

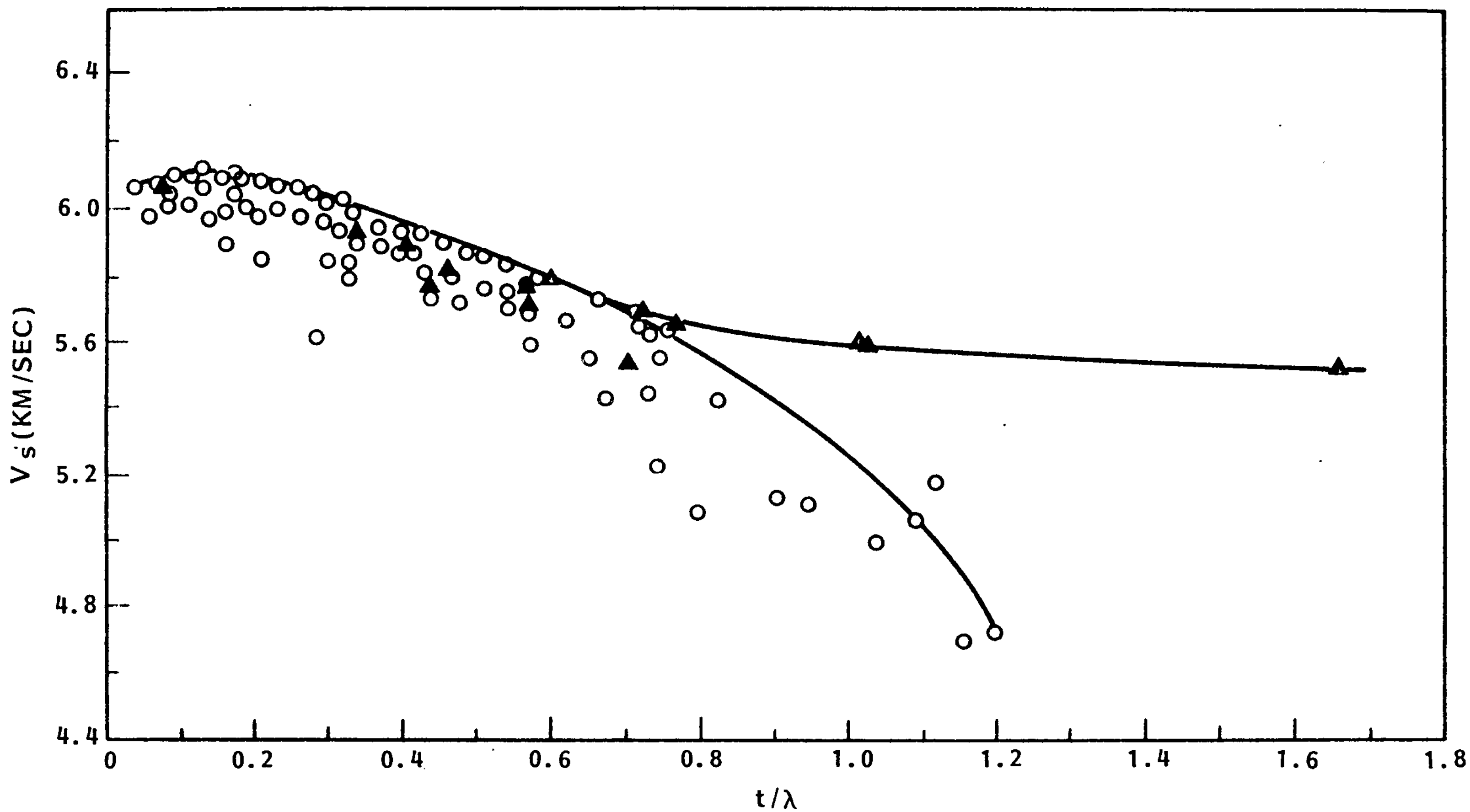
The fact that $A\ell N/A\ell_2O_3$ is a composite system leads to the property that several of the acoustic wave parameters are functions of the $A\ell N$ film thickness (t) to the wavelength (λ) ratio. The dependence of SAW velocity upon t/λ makes it possible to fabricate SAW devices with different operating frequencies from the same photomask by varying the $A\ell N$ thickness. The temperature coefficients of delay and coupling coefficient are also a function of t/λ.

GROWTH OF ALUMINUM NITRIDE ON SAPPHIRE

The $A\ell N/A\ell_2O_3$ substrates that the 2.2 GHz SAW delay lines were fabricated from are not commercially available, but rather were grown specially at TRW for this program. Aluminum nitride is grown epitaxially on the R-plane of sapphire substrates. The film is grown by a chemical vapor deposition process involving the reaction of a metal-organic gas $(CH_3)_3\ A\ell$ trimethyl aluminum (TMA), with ammonia in the presence of hydrogen. The process is performed at a temperature of approximately 1200^oC, which is achieved using RF heating.

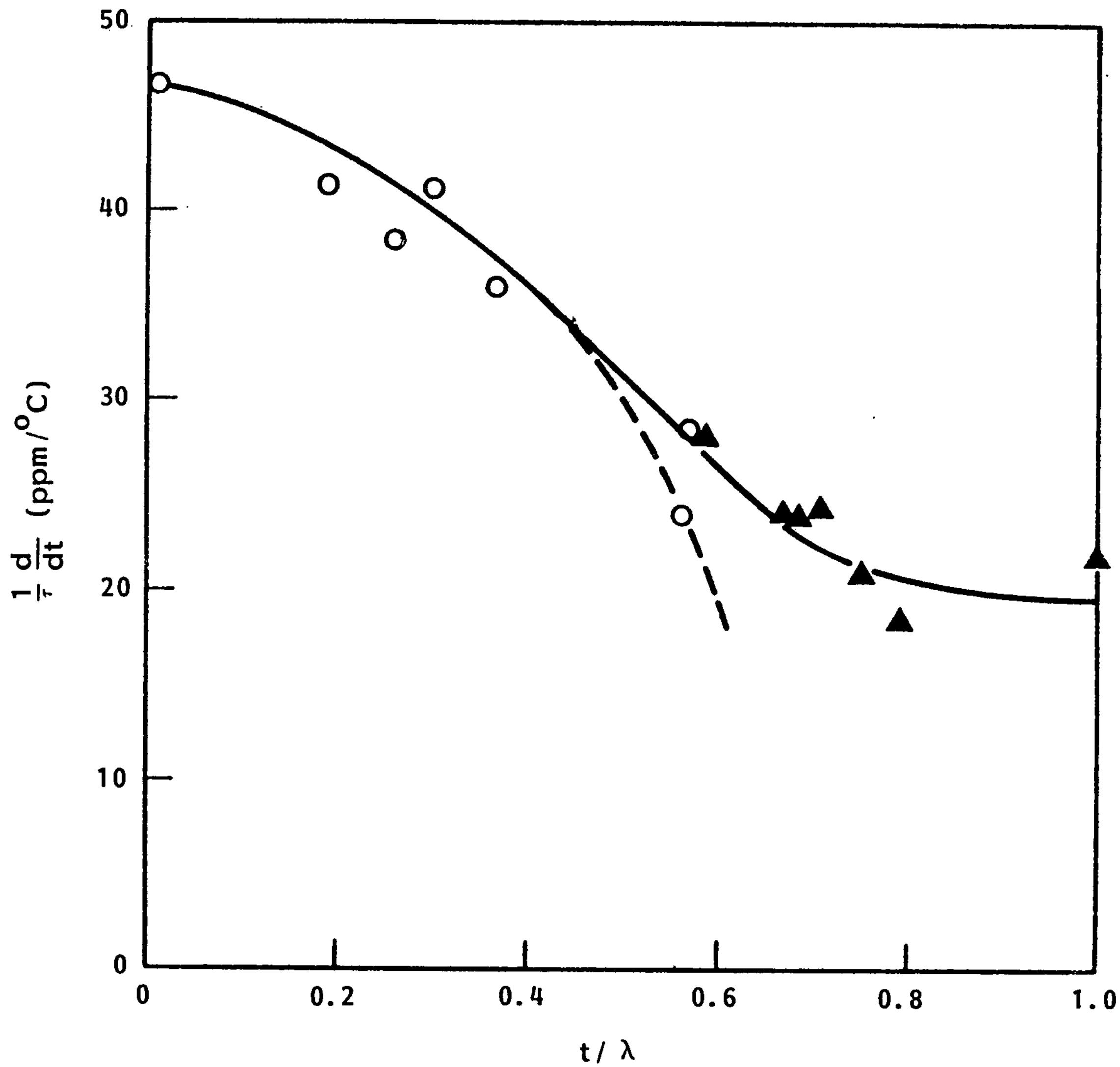
SAW PHASE VELOCITY V_S VERSUS τ/λ, ALONG AℓN C-AXIS

TRW
DEFENSE AND SPACE SYSTEMS GROUP



TEMPERATURE COEFFICIENT OF PHASE DELAY VERSUS THE RATIO OF AℓN THICKNESS TO WAVELENGTH

TRW



SAW PHOTOGRAPHS

A 2.2 GHz SAW delay line mounted in a flatpack is shown. The SAW crystal is mounted using an RTV adhesive which serves to isolate the SAW crystal from mechanical stresses. Connections from the delay line to the package are made using aluminum bond wires which also provide inductive matching between the capacitive transducers and 50Ω. Prior to installation in an oscillator, the flatpack would be hermetically sealed.

The second photograph was taken from a scanning electron microscope at a magnification of 10,000 power. It shows the surface of the AℓN epitaxial film. The crystal surface shows excellent growth with structure alignment all in the vertical (C) axis. The thickness of the AℓN layer is approximately 3 μm.

SAW OSCILLATOR DELAY LINE DATA

The data for the SAW delay lines used in the two oscillators is tabulated in this summary. A typical swept insertion loss characteristic is also shown.

2.2 GHZ SAW OSCILLATOR DEVELOPMENT OBJECTIVES

The basic SAW oscillator design was examined in detail in order to develop the optimum circuit configuration. The two key design parameters were phase noise and efficiency.

An electronic temperature compensation circuit was designed and evaluated. The temperature compensation circuit electronically compensates the SAW oscillator to correct for the delay line frequency drift over temperature.

Two deliverable 2.2 GHz temperature-compensated SAW oscillators were fabricated. One of the oscillators was used as the reference source in the Ku-band frequency source while the other is available for long term evaluation.

A detailed characterization of the two SAW oscillators was performed and the oscillator's phase noise, temperature, and aging parameters were measured.

2.2 GHZ SAW OSCILLATOR

The 2.2 GHz SAW oscillator has a number of advantages compared to conventional sources. The SAW oscillator is a fundamental oscillator which can operate at 2 GHz with low phase noise and high stability. Because the SAW is a fundamental oscillator, it does not require the multipliers, amplifiers, and filters normally required by conventional crystal multiplier sources. It has therefore, a considerable size, weight, and power advantage. In general, the SAW oscillator provides equivalent or superior performance compared to a bulk oscillator/multiplier chain with a significant savings in physical size, weight, and power.

The SAW oscillator developed under this program operates at 2.149 GHz with an output power of +17 dBm. It has been operated over a temperature range of 0° to 120°F. The phase noise of this unit is -102 dBc at 10 kHz from the carrier. It occupies 8.5 in^3, weighs 227 grams, and consumes 2.5 watts of dc power.

2.2 GHZ SAW OSCILLATOR DATA SUMMARY

Performance versus requirements for the 2.2 GHz temperature-compensated SAW oscillator is tabulated in this summary.

SURFACE ACOUSTIC WAVE OSCILLATORS

A SAW oscillator consists of a SAW delay line connected in a feedback loop with an amplifier. This configuration will oscillate at any frequency for which the total phase shift around the loop is an integer multiple of 2π, and the gain of the amplifier is equal to or greater than the net insertion loss of the feedback elements. Therefore, the SAW delay is designed as a bandpass filter such that amplitude and phase conditions required for oscillation are met at only one frequency. The desired SAW delay line filter response is realized by using both open and closed transducer structures in the fabrication of the delay line. The open and closed transducer responses are overlapped so that a minimum loss point occurs in both transduucers at only one frequency.

SAW OSCILLATOR TEMPERATURE COMPENSATION

Temperature compensation of the 2.2 GHz SAW oscillator is accomplished with an active electronic circuit. The SAW oscillator is a voltage controlled design in which the frequency can be shifted by changing the voltage supplied to a varactor phase shifter network. By applying an appropriate voltage to the frequency control input of the SAW oscillator, its frequency can be maintained constant with respect to varying temperature. The temperature compensation circuit generates the voltage-temperature function required to stabilize the SAW oscillator temperature characteristic. The temperature compensation circuit consists of a temperature sensing element (sensistor) which changes resistance with temperature. The varying resistance is converted to a voltage and conditioned by an LM108 operational amplifier to generate the proper correction voltage.

SAW OSCILLATOR TEMPERATURE DATA

The temperature data for the SAW oscillators are summarized in the two frequency-output power versus temperature curves and the temperature performance summary table.

PHASE NOISE PLOT

The phase noise of the 2.2 GHz SAW oscillator was measured by the TRW metrology department. The measurement covers the frequency range of 20 Hz to 1 MHz from the carrier. A typical 2.2 GHz SAW oscillator phase noise characteristic has been presented. The oscillator phase noise exhibits a 20 dB per decade slope and a noise floor of -160 dBc/Hz.

KU-BAND SOURCE OBJECTIVES

The overall objective of this task was to develop a high performance Ku-band source. Four specific tasks were addressed which are a part of the overall goal.

A source configuration study was performed to identify the optimum Ku-band source configuration. The conclusions drawn from this task identified the baseline configuration for the Ku-band source.

The design and fabrication of the baseline Ku-band source was the second major task. The third task was the complete characterization of the baseline source design. The final task involved the fabrication and evaluation of the TED devices. The TEDs were evaluated as Ku-band frequency dividers.

CONFIGURATION STUDY

A detailed configuration study was performed in order to objectively compare the potential performance and risks involved with two possible circuit approaches. The results of this study determined the baseline design approach to be used on the Ku-band source.

The two possible circuit approaches include either frequency multiplication or division in order to achieve phase comparison between the 2 GHz SAW oscillator and the 15 GHz FET VCO. The multiplier approach multiplies the lower frequency reference to the output frequency, while the divider technique divides the output frequency to the reference frequency.

The two techniques were compared on the basis of both physical and electrical characteristics. The particular parameters considered were size, weight, power, complexity, temperature performance, and phase noise.

X7 MULTIPLIER APPROACH

The X7 multiplier source multiplies the 2.2 GHz reference signal by seven to generate a 15 GHz reference signal. The phase comparison between the 15 GHz multiplied reference signal and the 15 GHz VCO signal is accomplished with a 15 GHz phase detector.

The X7 multiplier requires a fairly high input level, +17 dBm at 2.2 GHz. An amplifier is required to raise the SAW oscillator's output level to the +17 dBm level. The input amplifier in the actual hardware has been designed into the SAW oscillator. The 15 GHz output signal, at a +5 dBm level, is used to drive the reference input port of the 15 GHz phase detector. The signal input from the phase detector is obtained from a power divider on the output of the 15 GHz FET voltage controlled oscillator (VCO). The phase detector output is conditioned by the loop filter, F(s), and routed to the VCO's frequency control input. The 15 GHz FET VCO is therefore phase-locked to the 2.144 GHz input signal.

TED DIVIDER APPROACH

The TED divider circuit generates a 2.2 GHz signal which is phase coherent with the 15 GHz VCO signal. The phase comparison between the 2.2 GHz VCO signal and the 2.2 GHz reference signal is accomplished with a 2 GHz phase detector.

A 15 GHz signal at approximately 0 dBm is coupled from the VCO's output to the input of the TED divider circuit. The TED divider has an output of approximately -10 dBm at 2.2 GHz. The TED's output level is amplified to +7 dBm in order to drive the signal input of the S-band phase detector. The phase detector compares the 2.2 GHz signal with the 2.2 GHz reference input. The phase error output voltage from this phase detector is conditioned by the loop filter and routed to the 15 GHz FET VCO frequency control input. The FET VCO is therefore phase-locked to the 2.2 GHz reference signal input.

STUDY CONCLUSIONS

The results of the divider/multiplier tradeoff study revealed five areas in which one circuit had a distinct advantage over the other. In general, the TED is smaller, lighter, and consumes less power than the multiplier, and the multiplier has superior phase noise and temperature characteristics. Based on the results of this study, the multiplier approach was selected as the baseline design primarily due to the problems associated with operating the TED over temperature. The risk associated with solving the TED temperature problem outweighed the advantages of smaller size and lower power consumption.

FET VCO DESIGN GOALS

The major goals in designing the 15 GHz FET VCO were hybrid circuit compatibility and good phase noise performance so when phase-locked to a stable reference, the source would be comparble to the best crystal/multiplier sources currently available. Since FET oscillators are traditionally noisy, it was desirable to be able to design with the ability to predict the noise performance of the oscillator. A secondary goal was to develop a high Q resonator, a major factor in improving phase noise performance.

15 GHZ FET VCO DESIGN APPROACH

Several factors were considered in choosing a design approach for the FET VCO. Of prime concern was selection of an oscillator configuration which would allow straightforward design and analysis. The feedback loop approach was chosen over the negative resistance configuration since feedback loop analysis enabled expression of oscillator performance in terms of amplifier gain, saturation power, resonator Q, and loop loss. The oscillator VCO range only required compensation for frequency drift due to temperature; therefore, the tuning range could be very narrow. This was accomplished using a loop phase shifter. The narrow frequency range also allowed the use of a high Q resonant circuit in the feedback path to improve the noise performance. A hybrid compatible cavity resonator was selected due to its 5 to 1 Q advantage over the microstrip resonators tested. Microstrip circuitry bonded to the top of the cavity was coupled to the resonator using capacitive probes soldered to the microstrip and protruding down through the top of the cavity. Each of the functional elements in the loop was built in microstrip and characterized. The individual circuits were then integrated into a single housing and tested as an ocillator.

FET VCO

The FET VCO in its final configuration consists of three stages of FET amplifiers with their bias circuits, a 3 dB Lange output coupler, the thin cavity resonator, a varactor phase shifter for tuning, and two sections of adjustable length microstrip integrated into an 2.3 x 1.8 x 1.1 inch aluminum housing. The oscillator frequency was set to 15.0 GHz with an output power of +5.5 dBm. The oscillator frequency can be electronically tuned over ±3 MHz with a -13 to -2 volt tuning voltage. The dc power consumption was less than 175 mW from the +5 and -5.2 V power supplies. Phase noise at 100 kHz offset was -104 dBc/Hz, which compares favorably to traditional oscillators which use high Q cavity resonators. The output frequency can be easily adjusted by tuning the cavity. The 0.050 inch thick cavity can be integrated easily into an hermetic hybrid design along with the microstrip circuits using techniques demonstrated in this source, making an even more compact source. The phase noise characteristics of the source allow a high quality stable signal to be produced when the VCO is phase-locked to a stable reference.

15 GHZ FET VCO PERFORMANCE SUMMARY

The results of the final tests on the FET VCO are summarized in the performance summary table.

The temperature tests indicated that improvements in the cavity temperature coefficient and the phase shift range of the varactor phase shifter would be necessary for operation over the full temperature range. This can be accomplished by using an Invar cavity resonator and upgrading the phase shifter design.

X7 15 GHZ MULTIPLIER

The X7 15 GHz multiplier is a varactor design. The circuit has been fabricated on an alumina substrate using microstrip techniques. This construction technique is capable of being hybrid packaged, is small in size, and has an inherent high reliability. The multiplier produces a +5 dBm output at 15 GHz with a +17 dBm input signal at 2.144 GHz. The 3 dB output bandwidth is in excess of ± 300 MHz and it operates over a -10°C to +55°C temperature range. Output power stability is better than ± 0.5 dB and all spurious are >20 dB down.

15 GHZ PHASE DETECTOR

The MIC 15 GHz phase detector consists of a pair of phase detectors, 90^{o} hybrid, in-phase power splitter and two low pass filters. The phase detector has two outputs: a phase error output and a coherent amplitude output. The coherent amplitude output is used to turn off the phase-locked loop sweep circuits as a telemetry lock indicator. The phase detector is a metal strip on an alumina substrate structure and is formed by a pair of diodes mounted at the interface between a coplaner and slot transmission line. Two phase detectors, one with 90^{o} phase shifter, are fabricated within the phase detector circuit. The phase detector operates over a bandwidth in excess of ± 200 MHz with input levels of approximately +5 dBm. It is an adaptation of a MIC QPSK modulator.

KU-BAND FREQUENCY SOURCE PERFORMANCE SUMMARY

The performance for the complete Ku-band frequency source is summarized in this table. The Ku-band source consists of a 15 GHz FET VCO which has been phase locked to a 2.144 GHz temperature-compensated SAW oscillator.

KU-BAND FREQUENCY SOURCE

The complete breadboard Ku-band frequency source has been assembled on two standard aluminum plates. The upper plate contains the RF circuitry, the SAW oscillator, FET VCO , X7 multiplier, phase detector and the power divider. The lower plate contains the phase-locked loop and power regulation circuitry. All 15 GHz interconnections are made using semirigid coaxial cable. Low frequency signals are carried on flexible coaxial cable. The complete assembly forms a stand alone 15 GHz source requiring only a ±15 volt power supply.

TED DIVIDER OBJECTIVES AND SUMMARY

The overall objective of this task was to evaluate the TED as a possible frequency divider element as part of a Ku-band phase-locked source. In order to accomplish this overall objective, five specific areas were addressed.

The information gathered on previous 1 and 5 GHz TED designs were used to scale the design to 2.144 GHz. A mask was fabricated for the 2.144 GHz TED devices and two wafer runs made. The 2.144 GHz TEDs were evaluated as 15 GHz divide by seven frequency dividers to determine their usability as a frequency divider in a Ku-band frequency source.

The data obtained in this task indicated that the TED is not a practical circuit element at this stage of its development. The operation of the TED is very unstable with respect to temperature. Based primarily on the TED's temperature sensitivity, the device was not selected as the baseline design approach.

TED FREQUENCY DIVIDER

The basic element of the 15 GHz frequency divider is the TED device. The TED is a TRW developed n-type GaAs TED triode. The triode structure is formed by adding a gate structure between the TED anode and cathode terminals. The output frequency of the TED is determined by electrical length (transit time) between the anode and cathode of the device. An electron domain initiated at the cathode travels to the anode. The travel time of the domain determines the output frequency of the device. Once an electron domain has been formed, another domain cannot be initiated until it reaches the anode. Therefore, if the TED device is biased such that new domains are initiated by the injection of a signal into the gate structure, the device can be used as a frequency divider because the TED will not react to trigger pulses during its transition time. In the case of the 15 GHz divider, six input pulses are applied during the transition time and do not initiate a new electron domain. The seventh pulse arrives as the transit time has been completed and reinitiates a new electron domain.

TED DIVIDER DATA SUMMARY

The TEDs fabricated on this program were designed to operate at 2.144 GHz. The actual operating frequency was somewhat high, typically in the 2.1 to 2.4 GHz range. Operating voltages were in the range of 25 to 45 volts on the anode and 0 to -4 volts on the gate. To achieve a 10 MHz locking range, an input power in the range of 0 to -18 dBm was required with a resulting output power in the range of -10 to -20 dBm. Typical temperature characteristics for the gate voltage, frequency, and locking bandwidth are shown.